CREATING ROUND AND SQUARE FLATTOP LASER SPOTS IN MICROPROCESSING SYSTEMS WITH SCANNING OPTICS

Paper M305

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Abstract

Performance of various modern laser based micromachining techniques can be improved by applying square laser spots with uniform intensity distribution. And providing possibility of scanning of such a spot over whole working field with using popular 2- and 3-axis galvo mirror scanners is of great importance for many laser microprocessing technologies, like scribing, drilling vias in PCB, flat panel display repair. These tasks can be successfully solved with using the field mapping refractive beam shaping optics like *πShaper* and *Focal-πShaper*. Due to their unique features, such as low output divergence, high transmittance as well as extended depth of field these beam shapers provide a freedom in building an optimum optical system. Depending on the conditions of a particular technique it is possible to apply either a *πShaper* with imaging optics or a *Focal-πShaper* with focusing lenses. And important feature of these approaches is in easy adaptability to optical design of already existing material processing systems. There will be considered several optical layouts based on various refractive beam shapers *πShaper/Focal-πShaper* to generate square shaped laser spots of uniform intensity which sizes span from several tens of microns to millimetres. Examples of real implementations will be presented as well.

Introduction

Applying of refractive beam shapers with laser scanning optics is important in realizing various industrial laser technologies as well as techniques used in scientific and medical applications. Today the galvo mirror scanners with F-theta, telecentric or other lenses as well as gantry systems are widely used in different applications like micromachining, solar cell manufacturing, microwelding, drilling holes, selective laser melting and others which performance can be improved by applying of beam shaping optics.

Depending on an application either round or square laser spots are required, therefore optics of beam shaping systems should provide possibility to realize not only variable intensity distributions but also various spot shapes.

The essential feature of the refractive field mapping beam shapers is that they transform the laser beam profile in a control manner by accurate introducing and further compensation of wave aberration, therefore the resulting collimated output beam has low divergence and there is no deterioration of the beam consistency. On the other hand this allows to adapt the beam shapers to create the final laser spots of required shape and intensity profile.

In this paper there will be considered two approaches of building industrial optical systems on the base of refractive beam shapers: ***imaging*** of output of a *πShaper*, and ***focusing*** of output beams of *Focal-πShaper's* being optimized to generate round and square focused spots. Examples of real implementations will be presented as well.

Focusing and Imaging optical approaches

Focusing of a laser beam

The issues to choosing an appropriate beam shaping optical system with scanners when ***focusing*** of a laser beam with using F-theta lenses were discussed thoroughly in the papers[9,10], let's describe those of them that are important for further considerations.

Typical optical systems with using mirror scanners consist of following components: laser, beam-expander, scanning head and focusing lens.

From the point of view of optics the 2-axis scanning head presents a pair of flat mirrors turning the direction of optical path. The beam-expander is used

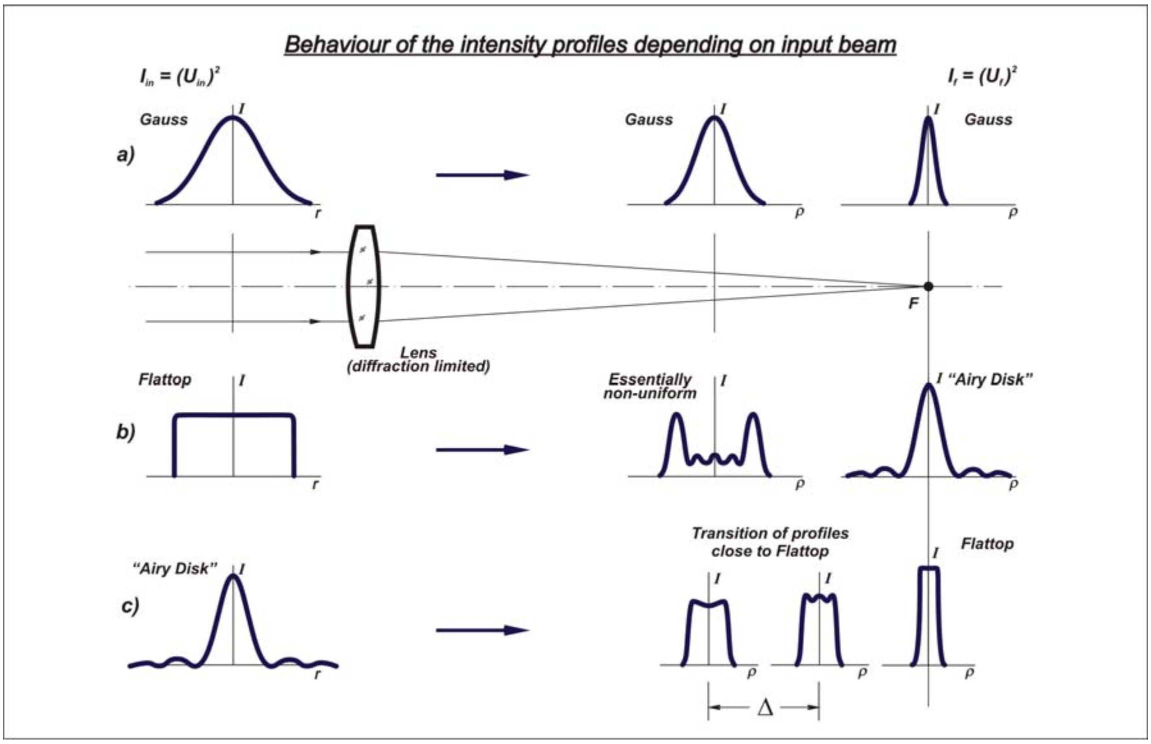

Fig. 1 Focusing of various laser beams by a lens.

when necessary to correct the beam size for further optical system, for example, to expand the beam for smaller final laser spot. To provide the spots, which size is comparable with wavelengths, the F-theta focusing lenses should have diffraction limited image quality over entire working field.

Details of behaviour of laser beam profile in zone of focal plane of a lens can be found in papers[2,5,9], here we emphasize on some important features.

According to the diffraction theory, the intensity distribution in a plane of analysis is result of interference of secondary wavelets. Since the conditions for interference change while a beam propagation *the intensity profile is variable and depends on the initial beam profile at the entrance of the focusing lens.*

Some important for practice examples of intensity profile behavior by *focusing* a beam is shown in Fig. 1:

- focusing of a TEM_{00} (Gaussian) laser beam,
- focusing of a flattop beam,
- creating a flattop spot in zone of focus of a lens,

Essential feature of focusing the Gaussian beam is that its intensity profile stays just Gaussian after the lens, only its size is varying! The spot in the focal plane of the focusing lens has intensity distribution described by Gaussian function, Fig. 1 a), this is a well-known feature widely used in laser technics.

But this remarkable feature of stable intensity distribution is valid for Gaussian beams only!

In case of a flattop initial beam, Fig. 1 b), the intensity profile $\boldsymbol{I_f}$ in focal plane is described by the function called as Airy Disk,

$$I_f(\rho) = I_{f0}\,[J_1(2\pi\rho)/(2\pi\rho)]^2 \qquad (1)$$

where $\boldsymbol{J_1}$ is the Bessel function of 1st kind, 1st order, $\boldsymbol{\rho}$ is polar radius in the focal plane, $\boldsymbol{I_{f0}}$ is a constant.

In the space between the lens and its focal plane the interference pattern gets strong variation both in size and in intensity distribution. The focusing of a flattop beam *never* leads to creating a spot with uniform intensity, neither in focal plane nor in intermediate planes. In other words: *If a particular application needs a laser spot of uniform intensity (flattop) there is no sense to focus a flattop beam!*

The technique of creating a flattop laser spot in focal plane of a lens is illustrated in Fig. 1 c). The intensity distribution at the input of a lens required to create a flattop round spot in the focal plane can be found by mathematical computations based on the inverse Fourier-transform technique, described for example in book[2]. The solution is just Airy Disk function, analogous to one in formula (1). This means: *a flattop laser spot in the focal plane of a lens is produced when the input beam has intensity distribution described by the Airy Disk function, so essentially non-uniform*. More detailed analysis[9] shows that in the space between the lens and its focal plane there are *variations of both the size and the intensity distribution*, and optimum, from the point of view of practice, working planes are shifted from the focal plane towards the lens. Creating of the beam with Airy Disk intensity distribution is the function of the field mapping beam shaper *Focal-πShaper*. As a rule this system is recommended to be applied when the final spot size is several microns or tens of microns, typically below 100 micron. Then it is reasonable to realize a ***focusing*** layout with setting up the *Focal-πShaper* ahead of the lens and scanning mirrors. This approach will be illustrated by examples later.

Imaging layouts

Another approach of generating the flattop laser spots is just creating an image of a certain uniformly illuminated aperture with using an ***imaging*** optical system. Let's consider a couple of optical layouts, Fig. 2, that are used in industrial equipment.

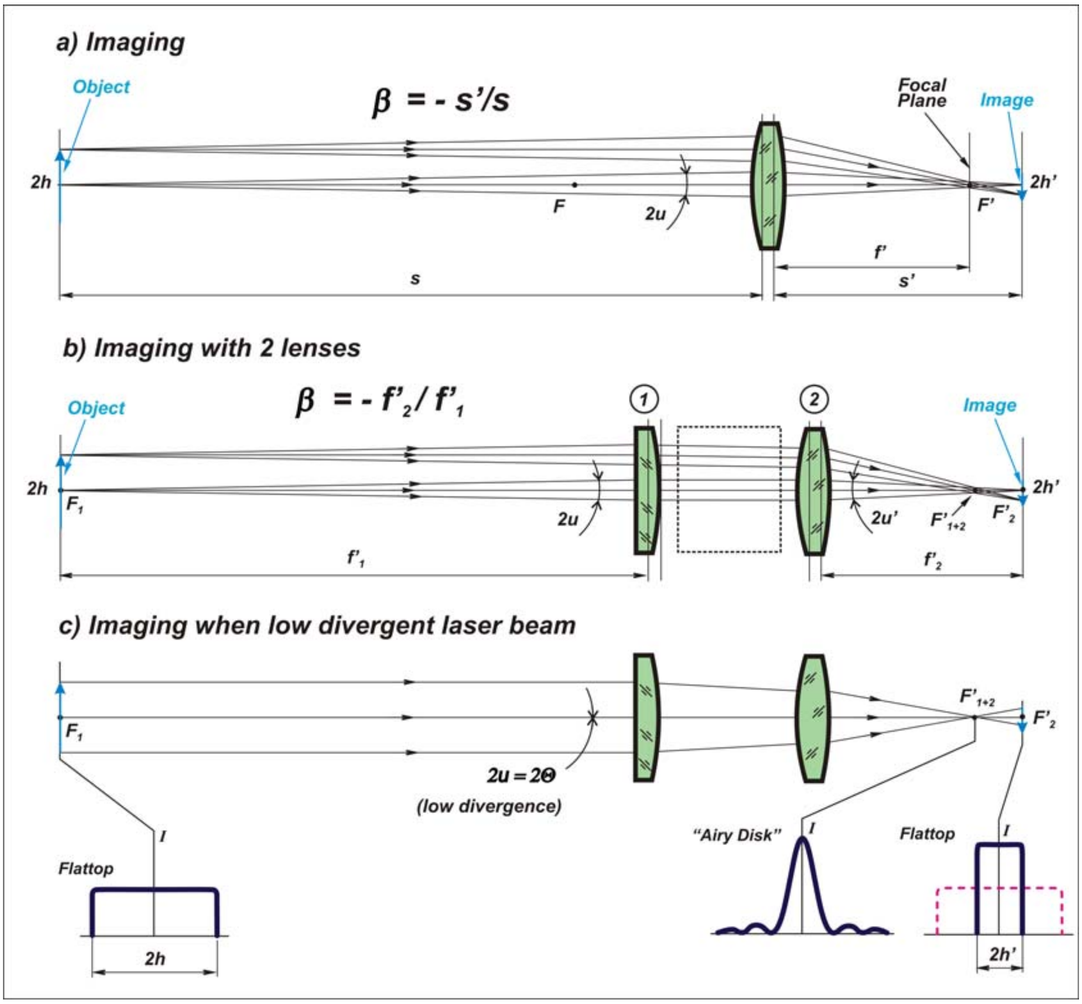

Fig. 2 Imaging layouts: a) Imaging with a single lens, example – microobjective lens,
b) 2-lens system, example - Collimator + F-theta lens, c) Intensity profiles when imaging a low divergent laser beam.

The first layout, Fig. 2a), presents an ordinary image formation with using a lens. Here the lens is just a singlet, sure, for high quality imaging a more sophisticated optical systems should be applied, for example aplanats (with correction of spherical aberration and coma), microobjective lenses. Calculation of parameters of a particular imaging setup can be done with using well-known formulas of geometrical optics, described, for example in book[6].

Let us note several important for practice issues:

- approximation of geometrical optics presumes that each point of the image is created by *a beam of rays* emitted by a corresponding point of the object,
- the object and image are located in *optically conjugated planes*, that means there is a same optical path length for all rays of a particular beam,
- the *real* image is always created after the lens focus,
- the transverse magnification β is defined as a ratio between distances from principal planes of the lens to, correspondingly, image and object:

$$\boldsymbol{\beta = -h'/h = -s'/s} \, , \qquad (2)$$

- the product of object size h and aperture angle u (exactly sin$u$) is constant all over the optical system:

$$\boldsymbol{h \cdot u = h' \cdot u' = const} \, , \qquad (3)$$

it is presumed here that an optical system is free of aberrations, for example, is aplanatic.

The imaging system can be also composed from two lenses, this approach is presented in Fig. 2 b). *The Object* is located in front focal plane of the lens *1*, thereby this lens works as a collimator producing a collimated beam from each point of object. The lens *2* focuses the beams and *the Image* is created in back focal plane of that lens; this can be, for example, an F-theta lens of a scanning optical system. The transverse magnification in this case can be calculated as a ratio of focal lengths of those lenses:

$$\boldsymbol{\beta = -h'/h = -f_2'/f_1'} \, , \qquad (4)$$

Please, pay attention, the common focus F'_{1+2} of the composed system is located between the lens *2* and its back focus F'_2, so the image is again located after the common focus of the entire system.

Since the beams from each object point are collimated in the marked by dashed line space between the lenses *1* and *2*, the distance between those lenses isn't critical and can be chosen from the point of view of design requirements of a particular industrial system. Here can, for example, a galvo-mirror scanning system be locating.

The last layout, Fig. 2 c), demonstrates the behavior of intensity profile of a low divergent laser beam in the above considered 2-lens imaging optical system. It is presumed here that the object is uniformly illuminated and a beam from each point of the object plane has low divergence, near the same like a laser beam of the similar size, $2u = 2\Theta$, – these features are typical for output beam of a refractive field mapping beam shaping system like *πShaper* which will be in more details described later.

Let's consider the transformation of the beam intensity distribution. In the optically conjugated image plane it will be similar to one in the object plane, this means if the intensity distribution is uniform in object plane it will be uniform in image plane as well; sure, the image size will be defined by the transverse magnification β.

The beam in object space has low divergence, hence, as discussed earlier (see comments to Fig.1 b), the intensity profile in the common focus F'_{1+2} will be described just by Airy disk function (1). In other words, being just a result of interference the intensity distribution in the common *focal plane* of imaging system is described by Airy disk while in the *image plane* – is similar to one in object plane. Evidently, this is valid also for other intensity profiles, for example the *πShaper* allow realizing also such profiles like "inverse Gauss" or super-Gauss[11] and these profiles will be reproduced in the image plane with a system magnification β.

The example in Fig. 2c shows also, that if a working plane is just the image plane, there is no need to take care for the intensity profile variation in other parts of optical path due to diffraction. Since the image is a result of interference of light beams being emitted by an object and diffracted according to physics of light propagation, it is necessary to take care to transmitting of full light energy through an optical system and avoid any clipping of a beam.

No doubts, the remarkable feature of the imaging system to repeat a beam profile in image plane can be used as a powerful tool in solving various optical tasks in microprocessing systems. By choosing parameters of an optical system it is easy to realize both magnified and de-magnified images. This imagining technique is typically recommended for the applications where final laser spots are of scale of millimeters, centimeter or meters, however it can be successfully applied to get laser spots of less than 100 micron size that is important in various micromachining laser techniques.

One can state the imaging technique shows the best results in achieving required size, shape and intensity profile of a final laser spot size, including getting round and square spots with uniform intensity and steep edges.

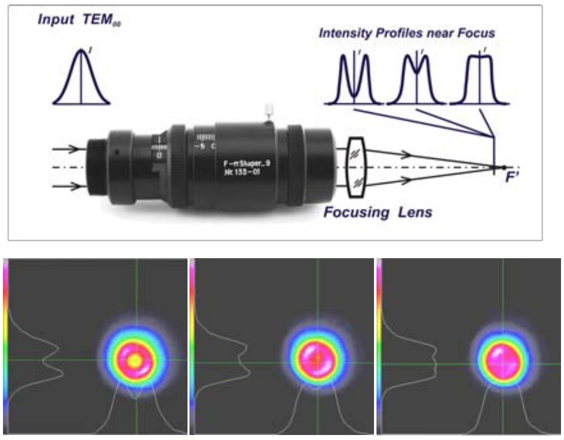

Fig. 3 Principle of the *F-πShaper* operation and examples of beam profiles.

Beam Shaping Optical Layouts

Focusing with using *Focal-πShaper*

The refractive field mapping beam shapers like *Focal-πShaper* provide at the output a beam which intensity distribution is described by Airy Disk function that is an optimum one to create a flattop spot in focal plane of a focusing lens. The operational principle is illustrated in Fig. 3.

Most important features and basic principles of the *Focal-πShaper* are:

- telescopic refractive optical systems transforming the Gaussian to Airy Disk intensity distribution;
- flattop, Doughnut, Inverse Gauss and other profiles can be generated by the same device;
- operation with input TEM_{00} beams;
- operation in a certain spectral band;
- optical design without internal focusing of a beam;
- movable optical components are intended to optimize the final spot intensity profile and to bring the plane of optimum profile in coincidence with the working plane of the system;
- compact design;
- easy integration to an optical setup and adaptation to a laser source;
- any diffraction limited focusing lens can be applied;
- wide range of distances between the *Focal-πShaper* and the lens.

Example of optical layout of focusing the laser beam with using the *Focal-πShaper* and scanning optics is presented in Fig. 4.

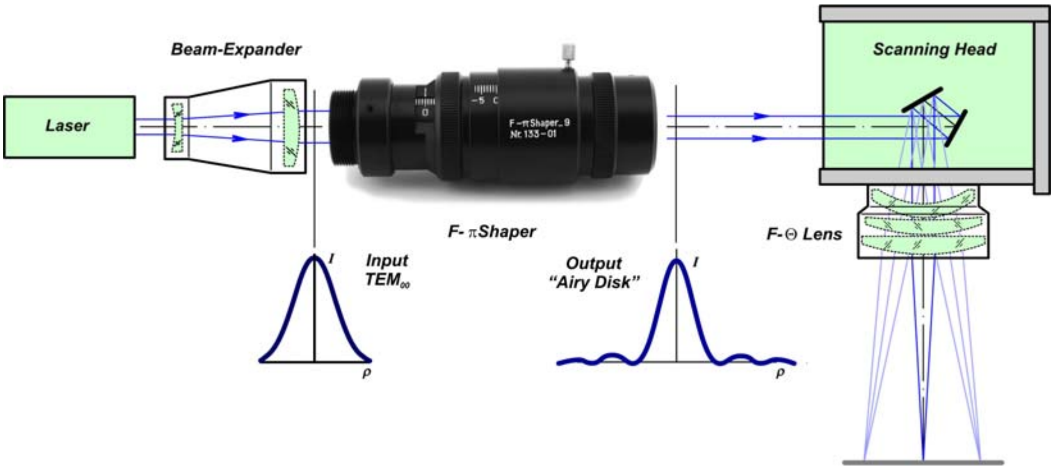

Fig. 4 *Focusing* Layout with using the *Focal-πShaper*.

Since the *Focal-πShaper* operates as a telescope with magnification about 1^x it can be easily integrated in existing optical systems ahead of the scanning optics. The distance between the *Focal-πShaper* and the focusing lens isn't critical; it can be chosen once but should be invariable during the system operation.

By varying the beam size at the entrance of the *Focal-πShaper* it is possible to vary the intensity profile of the final spot, therefore, variation of magnification factor of the beam-expander ahead of the *Focal-πShaper* is a good mean to provide Flattop, Donut and Inverse Gauss profiles. Choosing the plane of optimum profile and bringing it to the working plane of existing equipment can be easily and quickly done by rotating focusing ring of the *Focal-πShaper*.

The final spot size depends on the focal length of the focusing lens applied[9]. As result it is possible to create small spots down to *few microns size*, typically below 100 μm! Therefore this beam shaping technique is suitable for various applications of micromachining, scribing, selective laser melting, and various technologies of manufacturing the solar cells, laser marking and many others.

Imaging Layout on Base of *πShaper*

The design of refractive beam shapers of field mapping type like *πShaper* is well-known and described in literature[1,3,4,7,8,11], their operational principle is shown in Fig.5. Fig.6 presents example of beam shaping.

Fig. 5 Principle of the *πShaper* operation.

For purposes of further considerations let us summarize the main optical features of the *πShaper* systems:

- telescopic refractive optical systems to transform intensity distribution of a laser beam from Gaussian to flattop (or tophat, or uniform) one;
- the transformation is realized through the phase profile manipulation in a control manner, without deterioration of the beam consistency and increasing its divergence;
- the output phase profile is maintained flat, hence output beam has low divergence;
- optical systems of beam shapers consists of two refractive optical components, variation of the distance between the components is used to adjust a *πShaper* in a real optical setup;
- TEM_{00} or multimode beams applied;
- Output beam is collimated and resulting beam profile is kept stable over large distance;
- Galilean design without internal focusing beam;
- achromatic optical design - the re-distribution is provided for a certain spectral band.

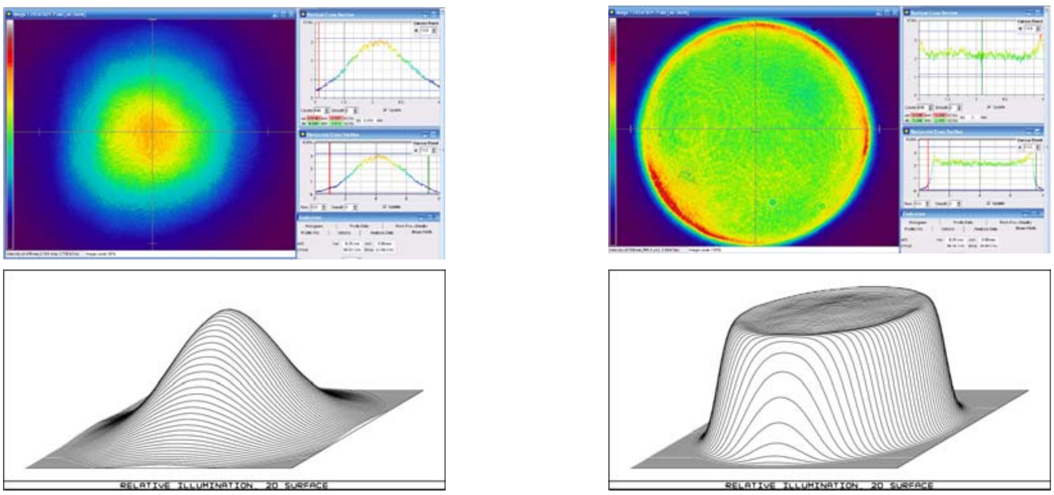

Fig. 6 Experimental and theoretical intensity profiles: Left – Input TEM_{00} beam, Right - after the *πShaper*
(Courtesy of Laser-Laboratorium Göttingen e.V.)

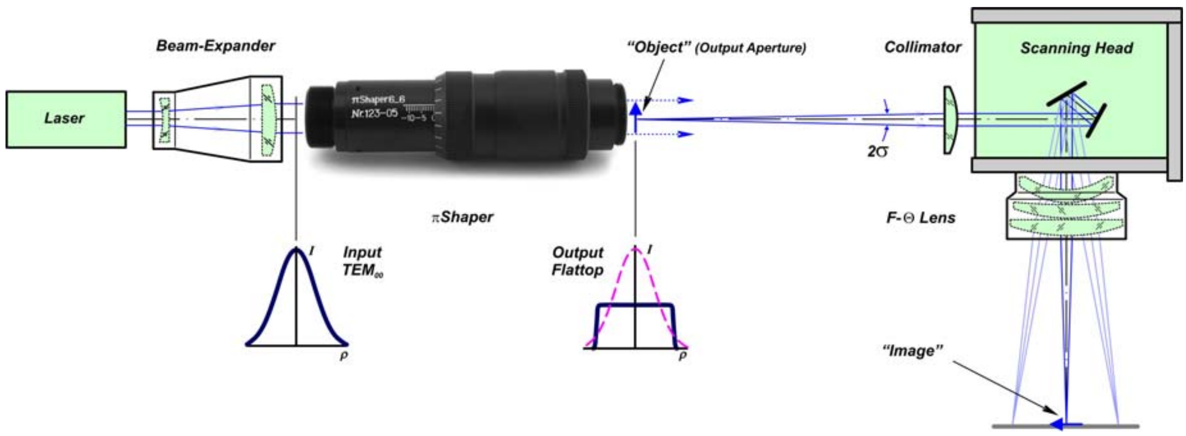

Fig. 7 Layout of *imaging* of the *πShaper* output aperture.

Typical output beam sizes of the refractive beam shapers is about 4.5- 12 mm and, as was discussed above, there is no sense to focus such a beam but it is possible to create flattop final spots by realizing the *imaging* approach. One of possible implementations of the basic 2-lens optical layout (Fig.2b) is presented in Fig. 7. Here the output aperture of the *πShaper*, where uniform intensity distribution is provided, is considered as an object, the collimator and F-theta lens compose an imaging optical system, and the 2-mirror scanning system is locating between those lenses. As we discussed above the distance between the collimator and F-theta lens isn't critical and any scanning head can be applied.

The *Object* at the exit of the *πShaper* can be implemented as a physical aperture or iris diaphragm, this means a real object, and then the *Image* will have very sharp edges and repeat the shape of that aperture. Evidently, the iris diaphragm will provide a simple way to vary the resulting spot size. If no apertures applied and output collimated beam simply propagates towards the imaging lens the *Object* has no a definite plane and whole space after the *πShaper*, where the intensity profile is flattop, will be mapped to a corresponding space on image side. Depending on the laser specifications like wavelength, M^2, beam diameter as well as *πShaper* model, the flattop profile of output beam is stable over hundreds of mm or even meters. Hence, the beam profile is stable over relatively long distance in the image space as well, in other words the extended depth of field (DOF) is provided. The DOF length can be approximately evaluated with taking into account that:

- longitudinal magnification of imaging system is equal to square of the transverse magnification[6],
- a virtual part of the output beam, on left side of the *πShaper* exit in Fig.2 and 7, to be considered as well, i.e. the length to be doubled.

Let's evaluate the transverse magnification that can be achieved in imaging systems based on widely used in industry optical components. Assume the working wavelength $\lambda = 532$ nm and the imaging optical system is composed from a collimator (lens 1 in Fig.2) and an F-theta lens (lens 2). Let the focal length of the F-theta lens $f_2' = 100$ mm and the entrance pupil diameter $D = 10$ mm, optical designs of modern F-theta lenses with such specifications allow to provide diffraction limited image quality over whole working angular field. Evidently, the aperture angle u' can be found as ratio of the pupil diameter and the focal length:

$$\boldsymbol{u' = D / 2f_2'} \,. \qquad (5)$$

On the other hand the double aperture angle $2u$ is defined by specifications of the beam shaping optical system providing beam profile in object space. In case of the refractive field mapping beam shaper *πShaper* it is the same like natural divergence of a laser beam: $2u = 2\Theta$. The angle of divergence Θ of a TEM_{00} laser beam is defined by the formula[6]

$$\Theta = \lambda \cdot M^2/(\pi \cdot \omega) \qquad (6)$$

where

- λ - wavelength,
- M^2 - laser beam quality factor.
- ω - a waist radius of the Gaussian beam.

Transforming the formulas (2), (3), (5) and (6) and taking the $\omega = h$, that is valid for most popular refractive beam shapers like *πShaper 6_6*, one can get a common expression for an achievable transverse magnification:

$$\beta = -2\lambda \cdot M^2 \cdot f_2'/(\pi \cdot \omega \cdot D) \qquad (7)$$

By substituting values of the considered example: λ = 532 nm, ω = 3 mm (for *πShaper 6_6*) M^2= 1, f_2' = 100 mm, D = 10 mm the calculations give the magnification down to 1/1000! In other words, theoretically with ordinary modern off-the-shelf industrial optical components and lasers it is possible to reduce drastically the output beam of a beam shaping system and provide resulting spot sizes of several tens of microns.

Large de-magnifying leads to large focal length of collimator. For example, if focal length of F-theta lens is given 100 mm, a *πShaper 6_6* is applied, so output beam diameter about 6 mm, and a required final spot size is 60 µm, then the transverse magnification to be $1/100^x$ that means the focal length of collimator to be 10000 mm! No doubts, this is difficult to realize in practice. Possible ways to make optical systems more compact are putting additional mirrors to bend optical path, realizing the collimator as a reverse telephoto lens, applying 2-step imaging. Some compact optical layouts realized in practice allow providing 200 times beam size de-magnifying.

The imaging approach with refractive beam shaper *πShaper* is typically recommended to be applied in applications where working laser spots are of size around 0.2-1 mm diameter, for example in microwelding, patterning on polymer layers, welding of polymers, laser marking; it is also used in some microprocessing applications like drilling vias in PCB, flat panel display repair where working laser spots of 30-50 micron size with both high flatness of intensity profile and high steepness of edges are required.

To choosing an optimum beam shaping layout

Both above considered optical layouts of creating small laser spots are used in various microprocessing techniques and choosing an optimum one for a particular application depends on features of that application. Comparing both approaches considered it is necessary to make some notes.

The focusing of beam with the Airy disk intensity distribution, provided by the *F-πShaper*, presumes optimizing conditions of interference in zone of focal plane of a lens. This approach allows providing flattop profile for central and periphery part of the spot, avoiding side-lobes, but the spot edges stay rather smooth. On the other hand, with the *F-πShaper* it is possible to realize a variety of profiles that makes it a powerful tool in optimization of parameters of a particular laser technology.

Due to operational principle the imaging of a flattop beam allows getting high edge steepness, especially when a physical aperture is used as an object. With a *πShaper* there is also some possibility to vary the output beam profile[11], but since it wasn't a main aim by the *πShaper* developing there is a less freedom in distribution variation comparing to the *F-πShaper*.

Summary of the features of focusing and imaging techniques, that are important for a right choice for a particular laser technology, is presented in the Table 1.

Table 1.

Features	*Focusing with F-πShaper*	*Imaging with πShaper*
Integration in equipment	No changes in machine design	Re-designing of optics required
Compactness of optical layout	Compact	Depends on magnification
Edge sharpness	-	+
Spots <100 µm	+	+
Spots >200 µm	-	+
Spot shape	Circle, square – defined by *F-πShaper* design	Arbitrary, defined by aperture shape
Losses*	Almost lossless	Round spot – lossless, Square spot ~30%

* - without the reflection and absorption losses

If using of an F-theta-lens with long focal length, say 255 or 400 mm, is required to cover a certain working field then most probable the *F-πShaper* is a solution. Such applications like scribing of thin-films, microwelding, firing the contacts, selective laser melting, marking, can also get benefits from providing with an *Focal-πShaper* profiles like inverse Gauss, or Donut, Fig.3.

If an application requires simultaneously high flatness of uniform intensity distribution and high steepness of edges of a round or square spot, it is rather recommended to apply imaging of an aperture located after a *πShaper*. These features are actual in drilling blind vias in PCB, flat panel display repair, some types of ablation of thin films.

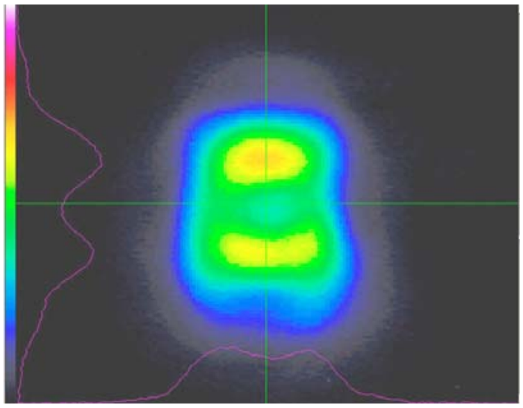

Fig. 8 Square spot of focused beam, *Focal-πShaper*.

Square spots

Till now we were discussing the round laser beam, but both considered techniques of *focusing* the beam with Airy disk intensity distribution and *imaging* the flattop beam can be applied to creating resulting laser spots of other shapes, for example a square one that is very important in some laser applications.

Creating of a flattop square spot by focusing optical approach requires re-designing of optical components of the refractive beam shaper *Focal-πShaper* and optimizing shape of aspherical surfaces. Modern technologies of optics manufacturing allow realizing these surfaces. Example of the focused spot with square shape, created in layout of Fig.4, is shown in Fig.8; here the *Focal-πShaper* with corresponding optical design was applied. The initial laser beam in that experiment was elliptic; therefore one can see difference is vertical and horizontal profiles. This method makes it possible almost *lossless* conversion of the round laser beam to square spots which size depends on focal length of a lens applied and can be *few microns or tens of microns*.

When imaging optical approach based on *πShaper* the task of creating a square spot can be easily solved by putting after the *πShaper* a square aperture serving as an *object* in the imaging system. Then the *image* in the focal plane of F-theta lens will be a square spot as well. The Fig.9 intensity profiles in a system done according to layout in Fig.7. The TEM_{00} laser beam at the entrance of the *πShaper 6_6* has circular shape and Gaussian intensity distribution, Fig.9 on left; therefore the round collimated beam after the *πShaper 6_6* has uniform intensity profile, Fig.9 centre. The square aperture to be installed at the *πShaper* exit is shown in Fig.9, centre by a dashed line; by this inscribed square the losses to be about 30%. Imaging of that square aperture with using a collimator and F-theta lens, see Fig.7, gives a resulting 50 x 50 μm^2 spot of square shape and flattop intensity profile, Fig.9, on right. Please, pay attention to *high steepness* of the spot edge. The high frequency intensity modulation in final spot comes from the modulation of the laser source. Operational principle of field mapping refractive beam shapers doesn't presume suppressing of that high frequency modulation, but when necessary it can be removed by using a spatial filtering before the *πShaper*.

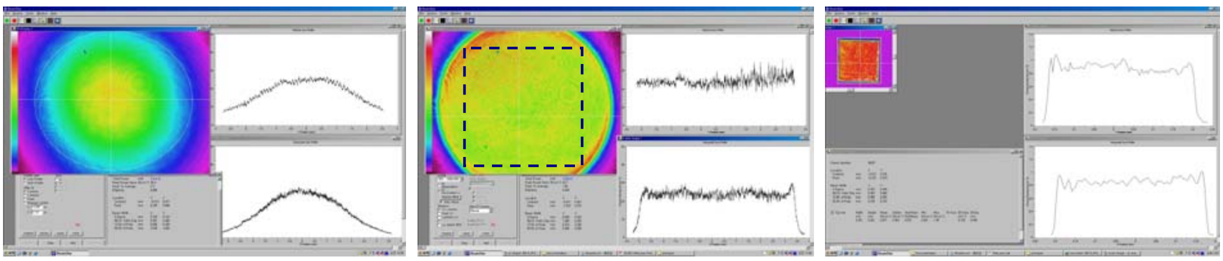

Fig. 9 Profiles in example of creating square spots with using *πShaper* and imaging system according to layout in Fig.7:
On left – input of *πShaper*, Centre - output of *πShaper*, On right – final square spot 50 x 50 μm^2.

Conclusions

To create round and square spots with flattop intensity for microprocessing technologies ***focusing*** and ***imaging*** optical approaches can be applied. In both cases there are used refractive beam shapers of field mapping type to realize required intensity profiles: *Focal-πShaper* is used to provide "Airy disk" for further *focusing* by a diffraction limited lens, *πShaper* is applied to get flattop beams being optimum for further *imaging*. Design features of these refractive beam shapers make it easy to combine them with scanning optics based on galvo mirrors and F-theta lenses with minimal changes in optical design of entire laser equipment or research installation. Depending on the features of a particular micromachining application: spot size and shape, edge steepness, working distance, required intensity profile, etc., one can build a solution on the base of available types of refractive field mapping beam shapers and other state-of-the-art optical components usually used in microprocessing systems with scanning optics.

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Acknowledgement

The authors are grateful to users of *πShaper* in Laser-Laboratorium Göttingen e.V., for their active and patient work with optics discussed in this paper and kind permission to publish some results achieved during their experiments.